WATER USE EFFICIENCY

Water Use and Root Length Density of *Cuphea* spp. Influenced by Row Spacing and Sowing Date

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ABSTRACT

Cuphea (*Cuphea viscosissima* Jacq. × *C. lanceolata* f. *silenoides* W.T. Aiton) is a potential new crop, but little is known concerning best agricultural management practices for this crop in temperate regions. A field study was initiated in Minnesota to determine the impact of sowing date and row spacing on soil water use and rooting characteristics of *Cuphea* spp. *Cuphea* spp. were sown on 4, 18, and 30 May 2001 and 30 April, 14 May, and 28 May 2002 in rows 200, 400, and 600 mm apart. Aboveground biomass, seed yield, and water use were bolstered by sowing *Cuphea* spp. in late April or early May rather than in late May. Water use for early sown and late-sown *Cuphea* spp. was respectively 366 and 311 mm. Sowing date also influenced water use efficiency (WUE) but only in 2002 when WUE of early sown and late-sown *Cuphea* spp. was respectively 1.87 and 1.64 kg ha^{-1} mm^{-1}. Sowing earlier in the spring also bolstered root growth as root length density in the upper 0.2 m of the soil profile was 24 km m^{-3} for the early sowing and 17 km m^{-3} for the late sowing. Row spacing did not affect seed yield, water use, or root length. This study indicates that biomass, seed yield, water use, and root growth of *Cuphea* spp. are favored by sowing early in the spring. Although early sowing resulted in greater water use, a tendency existed for *Cuphea* spp. to utilize water more efficiently in seed production when sown earlier in the spring.

C HEMICAL INDUSTRIES utilize medium-chain fatty acids (MCFA) to manufacture soaps and detergents, personal-care products, nutritional and dietetic products, and lubricants (Thompson, 1984). Medium-chain fatty acids such as caprylic (C8:0), capric (C10:0), lauric (C12:0), and myristic (C14:0) used to manufacture these products are presently derived from coconut (*Cocos nucifera* L.) and palm (*Elaeis guineensis* Jacq.) kernel oils and petrochemicals. Approximately 1.5 and 0.8 Tg of coconut and palm kernel oil, respectively, are imported into the United States and all other "developed" countries each year to meet the needs of industry for MCFA (FAO, 2003). There are no present domestic and renewable sources of MCFA in the United States.

Cuphea spp. (family Lythraceae) produce seed enriched in MCFA (Miller et al., 1964; Graham, 1989). *Cuphea* spp. are native to North, Central, and South America and until recently remained wild (Knapp, 1993). Several of the 260 species of *Cuphea* identified to date are found in temperate climate regions (Graham, 1989)

and exhibit favorable agronomic characteristics (Hirsinger, 1985) that could result in a domestic and renewable source of MCFA.

Cuphea spp. largely thrive in tropical climates, but many species are also well adapted to regions that are moist and temperate. Indeed, the small taproot characteristic of these species likely limits their adaptation to wetter environments and is perhaps one morphological trait that induces wilting in the absence of water (Graham, 1989). A few species of *Cuphea* have been found in more arid environments; thick leaves or large taproots allow these species to cope with drought stress (Graham, 1989). Other morphological traits such as seed shattering and seed dormancy are wild-type traits that have hindered commercial production of *Cuphea* spp. However, germplasm lines of *Cuphea* that are nonshattering, nondormant, and self compatible have been developed over the past decade (Knapp, 1993).

In one of only two known field experiments to identify the best agricultural management practices for *Cuphea* spp. production, Gesch et al. (2002, 2003) assessed the impact of sowing date and row spacing on growth and seed yield of *Cuphea* spp. in the northern Corn Belt of the United States. Although plant population confounded the results of their study, *Cuphea* spp. produced more seed when sown in May rather than in April or June. Poor emergence resulted in low yield of *Cuphea* spp. sown in mid-April while enhanced interplant competition for available light, water, and nutrients contributed to low yield of *Cuphea* spp. sown in June. The researchers also found that *Cuphea* spp. sown in wide rows compensated for seed yield by producing more branches and seedpods than that sown in narrow rows. The other known experiment examined the impact of depth and rate of sowing on seedling emergence and seed yield of *Cuphea* spp. in Iowa (Roath, 1998). Emergence, and thus seed yield, was favored by sowing at a higher rate and at a shallower depth. Seed yield varied considerably across years; a crop failure resulted in no seed production in 2 of the 7 yr of the study. For the other 5 yr in which *Cuphea* spp. produced seed, yield (averaged across all treatments) varied from 52 to 705 kg ha^{-1}. No explanation was given for the interannual variation in seed yield. Roath (1998) did, however, suggest that intense rainfall events after sowing and seed shatter late in the season can cause poor seed yield.

Although *Cuphea* spp. have been grown successfully in the Corn Belt, availability of soil water appears to

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Abbreviations: MCFA, medium-chain fatty acids; WUE, water use efficiency.

be one environmental factor that may limit growth and seed production of *Cuphea* spp. (Arndt, 1985; Graham, 1989). Little information, however, exists that describes rooting characteristics and associated water use of *Cuphea* spp. Therefore, the objective of this study was to evaluate the influence of sowing date and row spacing on soil water use and rooting characteristics of *Cuphea* spp.

MATERIALS AND METHODS

This study was conducted at a field site located 24 km north northeast of Morris, MN (45°35′ N, 95°55′ W), and within the Prairie Pothole Region of North America; the region is characterized by rolling topography and landscape depressions formed during the last glaciation. Experimental plots were established on a Barnes loam (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) with a 0.5 to 4% slope in 2001 and ≤0.5% slope in 2002. The field site was previously in *Cuphea* spp. and soybean before establishment in 2001 and 2002, respectively. One day before sowing, 110 kg N ha^{-1}, 12 kg P ha^{-1}, and 30 kg K ha^{-1} were broadcast and incorporated across the site.

Cuphea spp. were sown on 4, 18, and 30 May 2001 and 30 April, 14 May, and 28 May 2002. These dates represent an early, normal, and late sowing date for crops typically grown in the region. Seed was sown at a depth of 13 mm and at an interrow spacing of 200, 400, and 600 mm using a grain drill. Seed was sown at 0.85 g seed m^{-1} row, or an equivalent rate of 42, 21, and 14 kg ha^{-1} for the respective 200-, 400-, and 600-mm row-spacing treatments. The soil surface was compacted with a roller packer after sowing to ensure good contact between the seed and soil. Main treatments (sowing date) were established in 6- by 18-m plots and split to accommodate secondary treatments (row spacing). Individual plots were 6 by 6 m. Three replications were included in the experimental design. At the time of emergence (i.e., no change in plant population according to observations made every other day), each plot was thinned by hand to establish a population of 400 000 plants ha^{-1}, or an equivalent intrarow plant spacing of about 120, 60, and 40 mm for the respective 200-, 400-, and 600-mm row-spacing treatments.

Instrumentation to measure soil water content and soil water potential was installed in each plot immediately after sowing. Soil water content was assessed weekly in each plot by neutron attenuation and at the beginning and end of the season by gravimetric sampling. Neutron access tubes were installed both within and between seed rows. Soil water content was determined at 0.3-m depth increments to a depth of 0.9 m. Soil matric potential was measured using tensiometers placed at a depth of 1.0 and 1.25 m in one replication of each sowing date treatment and all plots with 400-mm interrows (total of 15 plots). These measurements, made weekly, aided in determining the direction and magnitude of water flow below the root zone.

Water use (WU) was determined by:

$$WU = P \pm \Delta SW - RO \pm WFBR \qquad [1]$$

where *P* is precipitation, ΔSW is change in soil water content, RO is water loss due to lateral surface water flow (i.e., runoff), and WFBR is water flow below the root zone. Runoff was assumed negligible due to few intense rainfall events (three events in 2001 and four events in 2002 exceeded 30 mm d^{-1}), no visual rills or washing of debris at the soil surface immediately following these rainfall events, and nearly level topography. Precipitation, soil water content, and water flow below the root zone were measured from emergence to harvest. Precipitation

was measured daily at a nearby microclimate station (100 m from the experimental plots). Water flow below the root zone was determined according to:

$$WFBR = -k(\Delta h/\Delta z) \qquad [2]$$

where *k* is the hydraulic conductivity (cm s^{-1}) and Δh is the difference in hydraulic potential (cm) over the depth interval Δz (cm). Hydraulic conductivity was assumed to vary with soil water matric potential according to Campbell (1985):

$$k = k_s(\psi_e/\psi)^{(2+3/b)} \qquad [3]$$

where k_s is the saturated hydraulic conductivity (cm s^{-1}), ψ_e is the air entry matric potential (cm) equivalent to the intercept of the natural log of the water retention curve, ψ is the matric potential (cm), and *b* is the slope of the natural log of the water retention curve. Saturated hydraulic conductivity was determined using the constant head method (Klute and Dirksen, 1986) on soil cores samples extracted from a depth of 1.00 to 1.05 and 1.20 to 1.25 m in all plots sown in mid-May. These same samples were used to determine water retention characteristics using a pressure plate apparatus (Klute, 1986).

Root length density was assessed on 26 July 2001 and 5 Aug. 2002 for the early sowing, 1 Aug. 2001 and 9 Aug. 2002 for the mid-May sowing, and 15 Aug. 2001 and 16 Aug. 2002 for the late-May sowing. These dates correspond to the onset of seed filling (seeds visible in the oldest pods). Soil core samples (32-mm diam.) were extracted to a depth of 0.6 m. Excavations made in 2000 (the year before the initiation of this study) indicated that *Cuphea* spp. had a small taproot with few roots penetrating below 0.4 m. Soil core samples were collected within and between rows at four locations in each plot. Samples were sectioned to ascertain root length density at depths of 0 to 100, 100 to 200, 200 to 300, 300 to 400, and 400 to 600 mm. The within-row and between-row samples collected in each plot were consolidated into one within-row and one between-row sample. Root length density was determined by the line intersect method (Bohn, 1979). This method required soaking the samples in softened water and extracting the root material by gently washing the material through nested sieves (nominal openings of 1.0 and 0.5 mm). Root and other organic material retained by the sieves were placed in a glass dish filled with water. A grid was placed beneath the dish, and root length was then determined by counting the number of roots that intersected each grid line.

Cuphea spp. were harvested on 9 Oct. 2001 and 8 Oct. 2002, which was respectively 3 d after and 1 d before the first killing frost (<–2°C) in autumn. Samples (1 m^{-2}) were clipped at the soil surface, bagged, dried at 60°C until constant weight, and threshed by machine. Seed separated by threshing was dried at 60°C, cleaned using a seed cleaner, and weighed. Final plant populations were obtained from the area harvested within each plot.

The experimental data were analyzed using a split-plot design in analysis of variance. Least significant difference (LSD) was used to separate treatment effects when significant *F* values ($P \leq 0.05$) were determined in the analysis of variance.

RESULTS AND DISCUSSION

Yield

Cuphea spp. yield, averaged across all treatments, was lower in 2001 than in 2002. Aboveground biomass, for example, was 6779 kg ha^{-1} in 2001 and 7491 kg ha^{-1} in 2002. In addition, seed yield was 537 kg ha^{-1} in 2001 and 653 kg ha^{-1} in 2002. The lower yield in 2001 corre-

sponded with less frequent and lower rainfall than in 2002. From emergence to harvest and averaged across sowing dates, rain (>0.2 mm d^{-1}) occurred on 29 d in 2001 and on 42 d in 2002. In addition, 304 mm of rain was received in 2001 while 354 mm of rain was received in 2002. Mean air temperature from emergence to harvest was the same (19.5°C) in both years. The lower aboveground biomass and seed yield in 2001 also corresponded with lower plant survival during the 2001 than the 2002 growing season. Although *Cuphea* spp. stands were thinned to 400 000 plants ha^{-1} at the time of emergence in both years, the number of plants harvested was 297 710 plants ha^{-1} in 2001 and 344 866 plants ha^{-1} in 2002.

Aboveground biomass diminished as sowing date was delayed in the spring (Table 1). Biomass production, however, was not influenced by interrow spacing as the probability of a type I error (probability of wrongfully rejecting the equality of treatment means) was 0.65 in 2001 and 0.24 in 2002. This lack of response in production to row spacing was also observed by Gesch et al. (2003), who reported that *Cuphea* spp. grown in wider rows compensated for yield by producing more branches. *Cuphea* spp. aboveground biomass declined from 8055 kg ha^{-1} for the early-May sowing and 7068 kg ha^{-1} for the mid-May sowing to 5213 kg ha^{-1} for the late-May sowing in 2001 (LSD = 1384 kg ha^{-1}). In 2002, biomass production ranged from 7816 kg ha^{-1} for the late-April sowing and 7879 kg ha^{-1} for the mid-May sowing to 6777 kg ha^{-1} for the late-May sowing (LSD = 905 kg ha^{-1}). No differences were apparent in biomass production when sown between late April and mid-May in both years. Like aboveground biomass, seed yield was also greater for *Cuphea* spp. sown in late April or early May than in late May in both years. In 2001, seed yield was 647 kg ha^{-1} for the early-May sowing, 539 kg ha^{-1} for the mid-May sowing, and 424 kg ha^{-1} for the late-May sowing (LSD = 118 kg ha^{-1}). Seed yield in 2002 ranged from about 710 kg ha^{-1} for the late-April and mid-May sowings to 542 kg ha^{-1} for the late-May sowing (LSD = 72 kg ha^{-1}). Interrow spacing did not influence seed production of *Cuphea* spp. as the probability of a type I error was 0.79 in 2001 and 0.38 in 2002. Harvest index, or the ratio of seed yield to aboveground biomass, did not vary with sowing date or row spacing in this study (probability of a type I error was 0.60 for sowing date and 0.37 for row spacing in 2001 and was 0.10 for sowing date and 0.22 for row spacing in 2002). The harvest index ranged from 0.080 in 2001 to 0.087 in 2002. These indices are similar to those derived from data presented by Gesch et al. (2002); those derivations indicate a harvest index that ranged from 0.056 to 0.081 for *Cuphea* spp. grown in Minnesota.

Differences in biomass production and seed yield among sowing dates appear to be related in part to differences in plant survival during the growing season. At the time of harvest in 2001, plant populations were 375 710 plants ha^{-1} for the early-May sowing, 313 382 plants ha^{-1} for the mid-May sowing, and 230 178 plant ha^{-1} for the late-May sowing (LSD = 73 437 plants ha^{-1}). In 2002, plant populations varied from 377 915 plants

Table 1. Yield of *Cuphea* spp. influenced by sowing date and interrow spacing over two growing seasons near Morris, MN.

Year	Sowing date	Row spacing	Biomass	Seed yield	Harvest index
		mm	—— kg ha^{-1} ——		
2001	4 May	200	8438	709	0.086
		400	7591	653	0.086
		600	8137	580	0.071
	18 May	200	6853	563	0.083
		400	7350	532	0.073
		600	7000	523	0.074
	30 May	200	5639	473	0.085
		400	4366	353	0.083
		600	5634	446	0.081
	LSD†		1384	118	NS‡
2002	30 April	200	7667	695	0.091
		400	7900	714	0.088
		600	7883	722	0.092
	14 May	200	8295	675	0.082
		400	8506	769	0.091
		600	6836	618	0.084
	28 May	200	7358	618	0.084
		400	6467	462	0.072
		600	6507	546	0.086
	LSD		905	72	NS

† LSD for sowing date treatment effects.
‡ No significant difference.

ha^{-1} for the late-April sowing and 369 784 plants ha^{-1} for the mid-May sowing to 288 665 plants ha^{-1} for the late-May sowing (LSD = 46 233 plants ha^{-1}). These plant populations explained 95% of the variability in aboveground biomass production and 92% of the variability in seed yield as determined by linear regression analysis. In addition, environmental conditions were less stressful and more conducive to plant growth and survival when sown early in the spring. This is exemplified by greater seasonal precipitation and more frequent rainfall events when *Cuphea* spp. were sown earlier in the spring. Precipitation from emergence to harvest in 2001 amounted to 335 mm from 33 events for the early-May sowing, 314 mm from 29 events for the mid-May sowing, and 263 mm from 24 events for the late-May sowing. In 2002, precipitation amounted to 371 mm from 45 events for the late-April and mid-May sowings and 319 mm from 37 events for the late-May sowing. Precipitation explained 82% of the variability in plant population whereas frequency of rainfall events explained 46% of the variability in plant population. Other factors such as disease, insects, and weeds can also influence production, but little documentation exists regarding diseases and insects that may affect *Cuphea* spp. growth, survival, and productivity. There were no visual indications of disease or insects that may have impaired production during the two growing seasons. Weeds were cultivated or pulled by hand during the course of the experiment and therefore did not influence production, root growth, or water use of *Cuphea* spp. in this study.

Water Use and Water Use Efficiency

Crop water use was assessed in this study by examining water flow dynamics below the root zone (Eq. [1]). Soil water flow below the root zone depended on saturated hydraulic conductivity and water retention characteristics (Eq. [2] and [3]), both of which were found to be similar at the 1.00- to 1.05- and 1.20- to 1.25-m depths.

For example, saturated hydraulic conductivity was 1.9×10^{-4} cm s^{-1} (SE = 1.2×10^{-4}) at the 1.00- to 1.05-m depth and 3.7×10^{-4} cm s^{-1} (SE = 0.7×10^{-4}) at the 1.20- to 1.25-m depth. In addition, the slope of the water retention curve (natural log of the relationship between soil matric potential and volumetric water content) varied from 10.05 (SE = 0.59) for the 1.00- to 1.05-m depth to 11.79 (SE = 0.98) for the 1.20- to 1.25-m depth while the intercept of the water retention curve (i.e., air entry matric potential) varied from −1.5 cm or −0.15 kPa (SE = 0.05 kPa) at the 1.00- to 1.05-m depth to −1.6 cm or −0.16 kPa (SE = 0.07 kPa) at the 1.20- to 1.25-m depth. Therefore, water flow was determined using values of saturated hydraulic conductivity and water retention characteristics averaged across the two depth intervals.

Water flow below the root zone did not vary across treatments in 2001 and 2002. For sowing date treatments, net water flow in 2001 was downward at a rate of 0.12 mm d^{-1} (SE = 0.18) for the early-May sowing and 0.44 mm d^{-1} (SE = 0.13) for the late-May sowing while water flow was upward at a rate of 0.42 mm d^{-1} (SE = 0.26) for the mid-May sowing. In 2002, water flow was downward at a rate of 0.30 mm d^{-1} (SE = 0.14) for the early-May sowing and upward at a rate of 0.27 mm d^{-1} (SE = 0.47) for the mid-May sowing and 0.15 mm d^{-1} (SE = 0.37) for the late-May sowing. For row-spacing treatments, net water flow in 2001 was downward at a rate of 0.17 mm d^{-1} (SE = 0.38) for the 200-mm rows and 0.09 mm d^{-1} (SE = 0.18) for the 400-mm rows while water flow was upward at a rate of 0.22 mm d^{-1} (SE = 0.35) for the 600-mm rows. In 2002, water flow was upward at a rate of 0.48 mm d^{-1} (SE = 0.44) for the 200-mm rows and downward at a rate of 0.05 mm d^{-1} (SE = 0.20) for the 400-mm rows and 0.54 mm d^{-1} (SE = 0.67) for the 600-mm rows. Averaged across all treatments, net water flow below the root zone was downward at a rate of 0.047 mm d^{-1} (equivalent to 6 mm or 2% of total water use) during the 2001 season and upward at a rate of 0.041 mm d^{-1} (equivalent to 14 mm or 4% of total water use) during the 2002 season. Since water flow did not differ among treatments and water flow contributed little to seasonal water use, water flow below the root zone was excluded from further analysis in comparing seasonal crop water use among sowing date and row-spacing treatments.

Crop water use from emergence to harvest, and averaged over all sowing date and row-spacing treatments, varied from 328 mm in 2001 to 365 mm in 2002. Soil water extraction accounted for 7% of water use (or 24 mm) in 2001 and 3% of water use (or 11 mm) in 2002. Thus, *Cuphea* spp. extracted more soil water in years with less rainfall to meet the evaporative demand. Warmer atmospheric conditions did not accentuate water use in 2002 because mean seasonal air temperatures were nearly the same each year (19.5°C in 2001 and 19.6°C in 2002). Water use was likely greater in 2002 due to enhanced biomass production that was caused by more favorable precipitation in 2002 than in 2001. Precipitation from emergence to harvest was 304 mm in 2001 and 354 mm in 2002.

Crop water use was influenced by sowing date each

year (Table 2). Water use, however, was not influenced by interrow spacing (probability of a type I error was 0.11 in 2001 and 0.08 in 2002). Water use declined as sowing date was delayed in spring; in 2001, *Cuphea* spp. sown in early May consumed 355 mm of water, that sown in mid-May used 340 mm of water, and that sown in late May used 289 mm of water (LSD = 6 mm). In 2002, water use varied from 378 mm for the late-April sowing and 383 mm for the mid-May sowing to 333 mm for the late-May sowing (LSD = 4 mm). Although water use declined with sowing date, more water was extracted from the soil profile during the growing season by *Cuphea* spp. that were sown later in the spring. For example, in 2001, *Cuphea* spp. sown in early May extracted 20 mm of soil water while that sown in mid-May and late May extracted 26 mm of soil water. In 2002, *Cuphea* spp. sown in late April extracted 7 mm of soil water while that sown in mid-May and late May extracted 12 and 14 mm of soil water, respectively.

Water use efficiency, or the ratio of seed yield to water use, ranged from 1.2 to 2.0 kg ha^{-1} mm^{-1} across all treatments in this study (Table 2). These values are relatively low compared with other oilseed crops. For example, WUE of canola (*Brassica rapa* L.) varies between 2 and 10 kg ha^{-1} mm^{-1} (Grey, 1998; Miller et al., 2003; Nielsen, 1998) while that of sunflower (*Helianthus annuus* L.), soybean, and mustard (*Brassica* spp.) is about 5 kg ha^{-1} mm^{-1} (Berglund, 1995). Flax, however, has a WUE similar to *Cuphea* spp. of about 2 kg ha^{-1} mm^{-1} (Berglund, 1995). Water use efficiency was lower in 2001 than in 2002. Averaged over all treatments, WUE was 1.63 kg ha^{-1} mm^{-1} in 2001 and 1.78 kg ha^{-1} mm^{-1} in 2002. The lower WUE in 2001 may be due to lower biomass production in 2001 than in 2002. Since biomass production is closely associated with leaf area in *Cuphea* spp. (Gesch et al., 2002), an assumed smaller leaf area likely accentuated evaporative loss from the

Table 2. Water use and water use efficiency (WUE) of *Cuphea* spp. influenced by sowing date and interrow spacing near Morris, Minnesota.

Year	Sowing date	Row spacing	Water use	WUE
			mm	kg ha^{-1} mm^{-1}
2001	4 May	200	354	2.03
		400	353	1.84
		600	358	1.60
	18 May	200	335	1.68
		400	340	1.56
		600	345	1.54
	30 May	200	290	1.63
		400	291	1.23
		600	286	1.54
	LSD†		6	NS‡
2002	30 April	200	376	1.85
		400	379	1.84
		600	378	1.91
	14 May	200	380	1.79
		400	385	1.98
		600	385	1.76
	28 May	200	330	1.87
		400	334	1.38
		600	335	1.66
	LSD		4	0.20

† LSD for sowing date treatment effects.
‡ No significant difference.

soil surface in 2001. Evaporative loss from the soil does not contribute to plant water uptake and thus would result in lower WUE.

The low WUE of *Cuphea* spp. is also likely influenced by the partitioning of dry matter between vegetative and reproductive development. In the present study, mean harvest index was 0.080 and 0.087 in 2001 and 2002, respectively. These values are considerably lower than those reported for other oilseed crops. For instance, the harvest index is around 0.50 for soybean (Ball et al., 2000), about 0.30 for canola (Hocking et al., 1997), and about 0.35 for sunflower (Zaffaroni and Schneiter, 1991). In addition, harvest indices for flax and mustard, which are about 0.20 to 0.25 (Hocking et al., 1997), are more than twofold greater than that of *Cuphea* spp. *Cuphea* spp. growth rate is slow during vegetative development but dramatically increases upon entering the reproductive phase (Gesch et al., 2001), which for field-grown plants in Minnesota, occurs around mid- to late July (Gesch et al., 2002). However, partly due to its indeterminacy, even during reproductive phase, *Cuphea* spp. divert much of their growth into vegetative dry matter accumulation. Hence, less dry matter is diverted into the seed, thereby reducing WUE.

Water use efficiency was influenced by sowing date, but only in 2002. Water use efficiency, however, was not influenced by row spacing either year (probability of a type I error was 0.32 in 2001 and 0.58 in 2002). In

2002, WUE declined as sowing date was delayed in the spring. Water use efficiency was 1.87 and 1.84 kg ha^{-1} mm^{-1} for the late-April and mid-May sowings, respectively, and 1.64 kg ha^{-1} mm^{-1} for the late-May sowing (LSD = 0.20 kg ha^{-1} mm^{-1}).

Root Length Density

Root length density was greater in 2001 than in 2002 (Fig. 1) despite the 10% higher biomass production and 22% higher seed yield in 2002 (Table 1). Root length density in the upper 0.2 m of the soil profile, and averaged across all treatments, was 23 km m^{-3} in 2001 and 21 km m^{-3} in 2002. Although the 2001 growing season was drier than the 2002 season, our results are similar to those of Hoogenboom et al. (1987) and Merrill et al. (2002), who found that root growth was stimulated by water stress or in drier years. Root length density of *Cuphea* spp. appears similar to soybean but smaller than other oilseed crops such as canola. Merrill et al. (2002), for example, found that the maximum root length density of oilseed crops in the northern Great Plains of the USA was about 45 km m^{-3} for crambe (*Crambe abyssinica* Hochst. ex R.E. Fr.), 35 km m^{-3} for canola and safflower (*Carthamus tinctorius* L.), 30 km m^{-3} for soybean, and 25 km m^{-3} for sunflower. They also reported considerable interannual variation in root length density that was attributed in part to differences in pre-
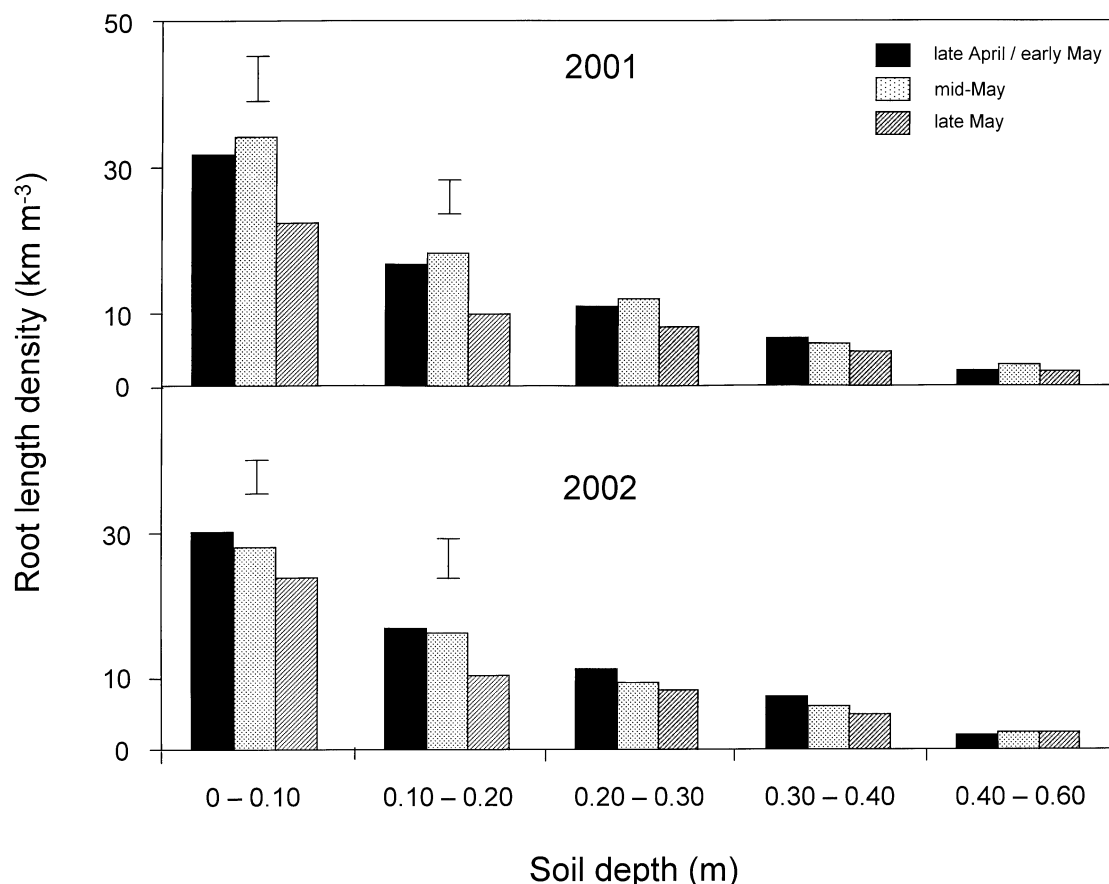

Fig. 1. Root length density of *Cuphea* spp. as a function of soil depth and as influenced by sowing date during the 2001 and 2002 growing seasons near Morris, MN. Vertical bars indicate least significant difference.

cipitation across years. Nickel et al. (1995) also reported a maximum root length density of about 30 km m^{-3} for soybean grown in Minnesota. Root length density, however, is not a constant and does vary as a result of plant genetic characteristics, plant development, soil physical and chemical properties, soil microbial community structure, foliar and root diseases, etc. For example, in contrast to the above root length densities, Johnston et al. (1998) reported a maximum root length density of about 10 km m^{-3} for soybean and about 100 km m^{-3} for canola in the upper 0.2 m of the soil profile.

Sowing date influenced root length density of *Cuphea* spp. in both years but only in the upper 0.2 m of the soil profile (Fig. 1). Root length density in the upper 0.2 m of the soil profile in 2001 (Fig. 1) was greater for the early-May (25 km m^{-3}) and mid-May (27 km m^{-3}) sowing than for the late-May sowing (17 km m^{-3}). In 2002, root length density for the late-April sowing (23 km m^{-3}) was greater than the late-May sowing (17 km m^{-3}). No differences in root length among sowing dates were found below a depth of 0.2 m. For example, for root length densities at a depth of 0.2 to 0.3 m, the probability of a type I error was 0.06 in 2001 and 0.14 in 2002. In addition, for root length densities at a depth of 0.3 to 0.4 m, the probability of a type I error was 0.16 in 2001 and 0.11 in 2002. Row spacing did not influence rooting characteristics throughout the soil profile in 2001 or 2002 (for root length densities in the upper 0.1 m of the soil profile, the probability of a type I error was 0.92 in 2001 and 0.07 in 2002).

CONCLUSIONS

Cuphea spp. favor early sowing in the spring in the northern Corn Belt. Seed production, water use, WUE, and root growth were bolstered by sowing early. Sowing early allows plants to transcend the critical stages of development before the occurrence of late-season water stress (wilting was observed in mid-August 2001). The meager root system (rooting depth of about 0.5 m and root length density of about 20 km m^{-3} in the upper 0.2 m of the soil profile) likely enhances the possibility for water stress to occur as soil water is depleted during the growing season. Supplemental irrigation or genetic improvement may be required to mitigate water stress and bolster seed yield before *Cuphea* spp. become a viable crop in the northern Corn Belt and an economic and reliable source of MCFA from American agriculture.

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